Space Plasma Ion Processing of Ilmenite in the Lunar Soil: Insights from *In-Situ* TEM Ion Irradiation Experiments

R. Christoffersen and L. Keller

Mail Code KR, ARES Directorate, NASA Johnson Space Center, Houston, TX, 77058 (roy.christoffersen-1@nasa.gov)

Role of Space Plasma Ion Processing in Space Weathering

•A key space weathering process is the alteration of the outer surfaces of regolith grains by two main classes phenomenon:

- •**SPACE PLASMA ION PROCESSING** – modification of the structure and chemistry of the outer rims of regolith grains by solar energetic ions, mainly those in the solar wind, but with contributions from more energetic ions such as coronal mass ejection ions and solar cosmic rays.
- •**SURFACE DEPOSITION** - deposition on grain surfaces of solid material condensed from micrometeorite impact vapors and/or vapors derived by solar ion sputtering of surrounding regolith.

•Progress on understanding space weathering can be made by studying these two classes of processes individually, or looking at their interactions, or both. How the relative importance of these two processes has varied over space and time on the lunar surface is of particular interest.

Space Plasma Ion Processing: More Quantitative Data Needed

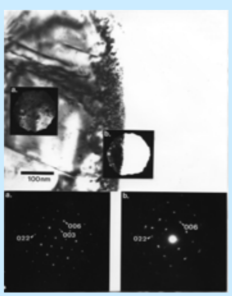
•For the moon at least, much is known from an observational perspective of how Space Plasma Ion Processing affects lunar regolith grains. For silicates (olivine, pyroxene, plagioclase feldspar) the most evident response to ion processing is **RADIATION INDUCED SOLID STATE AMORPHIZATION** of the outer margins of grains. This contributes either wholly or in part (the other part being vapor deposition) to characteristic formation of **AMORPHOUS RIMS** several tens to hundreds of nanometers thick on regolith grains.

•Although it is roughly known how much exposure time on the lunar surface is required to make a radiation processed grain rim, a more quantitative understanding of grain lifetimes on the lunar surface and many other aspects of space weathering could be obtained if we had better experimental data on ion-solid interactions in lunar minerals. Unfortunately these data have accumulated much more slowly in comparison to the results of observational studies.

•In particular, a key piece of data still needed for lunar minerals are precise measurements of the ion dose levels at which a given crystal structure undergoes the transition from the crystalline to the amorphous state. For many solids with complex crystal structures (such as silicates) this transition can occur abruptly once a critical level of radiation-induced structural defects is attained. The results is **CRITICAL AMORPHIZATION** at a **CRITICAL AMORPHIZATION ION DOSE**.

Ilmenite Versus Silicates: A Study in Radiation Processing Contrasts

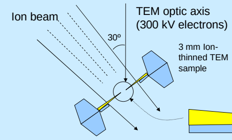
•The role of space plasma ion processing in lunar space weathering has a special interest story: the apparent resistance to solar ion radiation-induced amorphization shown by regolith ilmenite. Ilmenite responds



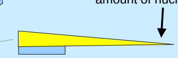
Experimental Approach: In-Situ TEM Irradiation Experiments

IVEM-Tandem Facility, Argonne National Laboratories

•650 kV NED ion implanter beam-line interfaced to Hitachi H9000NAR 300 kV TEM



Restrict TEM observation to thinnest grain edges (<500 nm thick) where ions completely penetrate sample and deposit a relatively uniform amount of nuclear collision energy



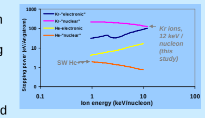
Materials Science Division
Argonne National Laboratory

Samples Investigated

- •Lunar ilmenite (ion milled grains 50um to 3 mm diameter in 70215 Hi-Ti Lunar Basalt)
- •Lunar clinopyroxene (ion milled grains w/ilmenite in 70215) Clinopyroxene
- •Synthetic Mg-pyroxene (En100, clinoenstatite, crushed grains on holey carbon)
- •San Carlos olivine (Fo90, ion milled single crystal)

Irradiation conditions

•IVEM-Tandem energy range is in "gap" between solar wind and solar cosmic ray energies, but provides "slow heavy" ions with high amorphizing potential. Used Kr ions with 12 keV/nucleon energy (1 MeV total energy) that deposit ~100 times more nuclear collsion energy (100 times taget atom displacements per ion) than solar wind He.



<table>
<tr><td colspan="6">In-situ ion irradiation TEM observations</td></tr>
<tr><td colspan="2">Kr ion dose (ion/cm^2)</td><td>1 x 10^{14}</td><td>5 x 10^{14}</td><td>1 x 10^{15}</td><td>7 x 10^{15} >> 8 x 10^{15} >> 9 x 10^{15} (final dose)</td></tr>
<tr><td colspan="2">Equivalent solar wind He (4 keV) dose (ions/cm^2)</td><td>4 x 10^{15}</td><td>2 x 10^{16}</td><td>4 x 10^{16}</td><td>2.8 x 10^{17} >> 3.2 x 10^{17}>> 3.6 x 10^{17} (final dose)</td></tr>
<tr><td rowspan="2">Ilmenite</td><td>Diffraction</td><td>no change (relative to starting material)</td><td>No change - strong discrete single-crystal pattern</td><td>Faint complex (non-circular) diffuse scattering intensity between strong main reflections</td><td>Faint circular diffuse ring intensity superimposed on strong main reflections; more complex diffuse scattering in some patterns; streaking along c*</td></tr>
<tr><td>Imaging</td><td>no change</td><td>Thinner outer edge of ion-milled grains completely amorphous, thicker regions show faint speckled/mottled strain contrast on 10-20 nm scale</td><td>Mottled BF contrast accentuated – but SAD indicates single-crystal structure</td><td>Amorphous grain edges reach steady-state width; thicker grain interiors show mottled BF contrast.</td></tr>
<tr><td rowspan="2">Pyroxene</td><td>Diffraction</td><td>no change</td><td>no change</td><td rowspan="2" colspan="2">Discrete reflections replaced by diffuse ring pattern – completely amorphous at 1 x 10^{15} and above</td></tr>
<tr><td>Imaging</td><td>no change</td><td>no change</td></tr>
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